



图灵原版电子与电气工程系列

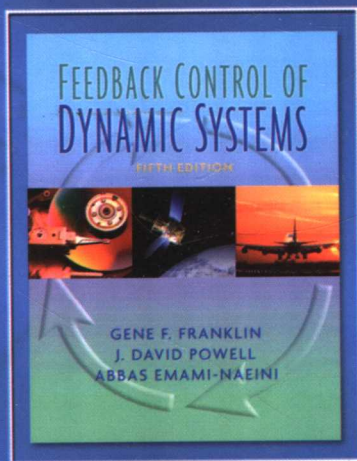


Feedback Control of
Dynamic Systems
(Fifth Edition)

自动控制 原理与设计

(英文版·第5版)

Gene F. Franklin
[美] J. David Powell 著
Abbas Emami-Naeini



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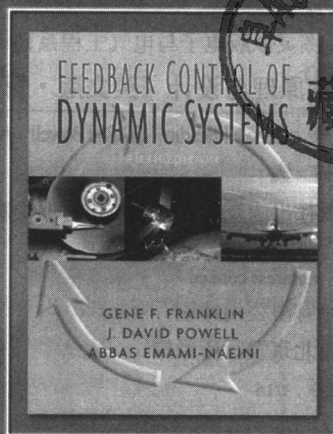
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内 容 提 要

本书是自动控制领域的名著,内容紧密围绕自动控制系统的分析与设计理论展开,主要介绍了自动控制的动态模型、动态响应、基本特性,着重介绍了自动控制的几种常规设计技术,还涉及了非线性系统的分析与设计,并穿插了许多自动控制在 MATLAB 下的仿真实例。

本书可作为高等院校自动控制及相关专业的高年级本科生和研究生的教材,还可供有关专业的教师、研究人员及从事自动控制相关工作的工程技术人员参考。

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谨以此书献给

Gertrude, David, Carole, Valerie, Daisy,
Annika, Davenport, Malahat, Sheila, Nima

前 言

本书这一版本依然针对控制理论的入门课程，并且保留了之前版本的优点。新版对描述反馈特征的第4章做了很大改动，内容安排更合乎逻辑，风格更为简约。本版还新增加了第9章非线性系统的内容，这一章把非线性问题零散的知识点集中在一起，组织成一个连贯的章节，并增加了部分新内容，第一次详细介绍这一重要领域。这种组织结构改善了之前把非线性系统内容随意散落在各个章节的情况。当然，希望更早地介绍这些内容的教师也可以轻易地做到这点。

本书的基本架构未变，依然包括利用根轨迹、频率响应和状态变量方程三种途径实现的设计分析，以及为阐明控制理论而精心准备的实例。跟过去一样，为了帮助学生检验学习效果，我们在每章的最后部分提供了复习题，并在本书的后面附有答案。

在介绍设计方法的三个核心章节里，依然希望学生能够掌握基本的手工计算方法，并能快速绘制出根轨迹或者伯德图的草图作为设计指导。然而，鉴于MATLAB软件在控制分析与设计中广泛的应用，本书较早介绍和使用了MATLAB。而且，鉴于越来越多的控制器在嵌入式计算机中实现，我们在第4章介绍了数字控制，并且在大量的反馈系统例子中对模拟控制器和数字控制器的效果进行了比较研究。一如从前，我们准备了一系列的MATLAB的“m”文件用来输出本书的图形，这些文件可以在如下网页的publications栏目下找到：

<http://www.scsolutions.com/feedbackcontrol.html>

本书将实例研究放在第10章，其内容涉及计算机硬盘的读写头控制和用于集成电路制造工艺中快速热处理器的硅片温度控制。

本版内容根据教学规律进行了安排，有助于提高学生对控制理论的兴趣，并为教师应对反馈控制入门课程教学的挑战打下了坚实的基础。

应对挑战

学生在自动控制学习中面对的有些挑战是长期存在的，还有些是近年来新出现的，有些挑战存在于工科学习的整个过程，有些是这门相对复杂的课程中独有的。无论挑战是旧有的还是新生的，普遍的还是特殊的，它们对本书的不断修订起到了非常关键的作用。下面逐一介绍这些挑战，并讨论我们的解决方法。

□ 挑战 掌握分析工具和设计方法

设计是工程尤其是控制系统的核心。学生们发现，有机会解决实践应用问题的设计课题会让人激动不已。但同时也会发现，由于设计问题给定的不足以及解决方案的不唯一，设计并不容易。由于设计对学生固有的重要性和激励性，整本书都对设计问题给予了相当的重视，从头开始树立解决设计问题的信心。

在学习了建模和动态响应的知识后,第4章将开始介绍设计问题。首先介绍的是反馈的基本思想,描述了它对稳定扰动、跟踪精度、参数变化时的鲁棒性的影响。随后,在根轨迹、频率响应和状态变量反馈技术的一致讨论中继续深入介绍设计方法。所有的论述旨在提供必要的知识,以找到一个在数学上便于理解的优秀反馈控制设计。

全书引用了大量的例子来比较不同设计方法所提供的设计技术的异同优劣。在集中研究实例的第10章,将以统一的方式采用所有方法来解决复杂的实际设计问题。

□ 挑战 新概念不断引入

控制是一个活跃的研究领域,因此,不断有新的概念、思想和技术涌入。其中一些因素很快就会发展到每个控制工程师都必须掌握的程度。本书将同时满足学生掌握传统以及现代知识的双重要求。

在过去的每一版中,我们都会尽力地平衡根轨迹、频率响应和状态变量设计法之间的学时分配。这一版继续强调对基本技巧的掌握,同时,也重视详细运算的计算机实现方法。考虑到数字控制器在目前领域中的重要地位,我们还将对数据采样和离散控制器的介绍提前。虽然跳过这部分内容对全书的流畅性并无损害,但是我们认为,让学生了解计算机控制的广泛应用程度以及计算机控制基本方法掌握的简易性,是十分重要的。

□ 挑战 需要运用大量信息

大量的系统都要应用反馈控制,控制问题的解决方案不断增多,这意味着今天的自动控制类学生必须掌握许多新的知识。学生们应如何在冗长复杂的理论学习中保持敏锐呢?如何确定重点和归纳总结?如何复习考试?帮助学生解决这些任务是第4版的准则,同样在第5版中会继续列出。

本书的特色环节如下:

特色环节	举 例
每章以总览和概述作为开始,从整体上说明每章主题在学科中的位置,并简要概括该章的内容	第3章开始,见第58页
斜体显示,将提示文章中的重要概念,也用来总结重要的设计程序	见第62页
一目了然的章节归纳,帮助学生复习并区分重点,简要地重申关键概念和结论	第2章,见第49页
设计辅助大纲。为方便查阅,将设计中 and 全书中用到的关系式集中在一处列出	书后插页
复习题,位于每章的末尾,答案附书后,指导学生自学	第2章,见第50页

□ 挑战 自动控制的学生来自广泛的学科

控制可应用于工程中可想到的任何领域,因此自动控制具有跨学科的特性。相应地,许多学校在各个传统学科分设了控制导论课程,而另一些学校,例如斯坦福大学,开设有一系列不同学科的学生共同参加的课程。但是,把实例限制于单个领域,则牺牲了反馈的广度和影响力,因此覆盖应用的整个范围是必然的趋势。本书体现了自动

控制的跨学科特性,为许多最普遍的技术提供素材以方便各学科学生使用。针对在状态转移分析方面有良好素养的电子工程学科的学生,我们在第2章介绍了机械运动方程的列写。而针对机械工程学生,我们在第3章回顾了用于控制理论的拉普拉斯变换和动态响应。另外,我们还简要介绍了其他方法。有时,还忽略其推导过程,而从响应的角度着眼于足够的物理描述,列写物理系统的动态方程。本书介绍的物理系统实例包括计算机磁盘驱动器的读写磁头、卫星跟踪系统、汽车发动机油-气比例调节和飞机的自动导航系统。

本书概要

本书共有10章和7个附录。一些章节的末尾安排有标注▲的高级、丰富的选学内容。基于上述内容的实例和问题也标注了▲。附录包括了背景资料和参考文献,如拉普拉斯变换表、复变量、矩阵理论以及各章末尾复习题的答案。

第1章介绍了反馈的核心思想以及重要的设计问题。这章还包括了从古老的过程控制到飞行控制和电子反馈放大器的控制理论简史。希望这份简史能够阐明该领域的发展过程,介绍对其发展起到重要作用的关键人物,以此激发学生的学习热情。

第2章简要地介绍了动态建模,涉及机械、电子、电机、流体以及热力学装置。这章是可以跳过的,其出发点是作为复习要点来帮助学生理清参差不齐的基础知识,或者可完全根据学生的需要来处理。

在第3章阐述了用于控制理论的动态响应。尤其对于电气工程专业的学生来说,这章的大部分内容也已经学过了。极点位置与暂态响应间的关系,以及附加零点和极点对动态响应的影响,对许多学生来说还是新知识。动态系统的稳定性在本章也会涉及。这些都需要认真学习。

第4章介绍了反馈的基本方程和传递函数,以及灵敏度和互补灵敏度方程的定义。利用这些工具,可以通过扰动抑制、跟踪精度以及误差敏感度对开环和闭环控制进行对比。根据跟踪多项式参考信号或者抑制多项式扰动的能力,系统分类可与系统类型的概念一起描述。最后,介绍经典的比例、积分、微分(PID)控制结构,探索控制器参数对系统特性的影响。在该章末尾的选修部分涉及了数字控制、PID整定和时域响应敏感度。

在第4章对反馈进行概述后,本书的核心内容,即基于根轨迹、频率响应和状态变量反馈的设计方法分别在第5章、第6章、第7章进行介绍。

第8章更详细地开发了一些在数字计算机中实现反馈控制设计所需的工具。

第9章介绍非线性内容,涵盖运动方程的线性化方法、变量增益的零记忆非线性分析、描述方程的频率响应、相平面、李雅普诺夫稳定性定理和循环稳定标准。

在第10章里,我们将三种主要的方法整合在几个实例当中,并建立了一个可应用于现实控制设计的框架。

课程结构

本书结构灵活。多数控制专业的大一学生可能已掌握了动态方程和拉普拉斯变换,因此,第 2 章和第 3 章可用作复习。在 10 周的学期中,可以复习第 3 章,学习第 1 章、第 4 章、第 5 章、第 6 章。其中大部分的选学内容可以忽略。在第二个 10 周的学期里,可以顺利完成第 7 章和第 9 章的学习,包括选学的内容在内。若忽略选学的内容,可以选择第 8 章的部分内容进行学习。一个学期能够顺利掌握第 1 章至第 7 章,如有必要也可包含第 2 章、第 3 章的复习内容。如果时间有余,学完这些核心内容后,可以学习第 8 章数字控制的部分内容、第 9 章非线性的部分内容和第 10 章的一些实例研究。

全书也可以实行三段 10 周教学法,分为建模和动态响应(第 2 章、第 3 章),经典控制理论(第 4 章、第 5 章、第 6 章)和现代控制理论(第 7 章至第 10 章)三个部分授课。

这两种基本的 10 周教学过程都已在斯坦福大学实践过,可应用于高年级的控制本科生和没有学习过控制的航空航天类、机械工程和电子工程类一年级研究生。初级课程复习第 2 章、第 3 章并学习第 4 章至第 6 章。高级课程为研究生设计,复习第 4 章至第 6 章,并学习第 7 章至第 10 章。这些顺序安排,补充了研究生课程在线性系统方面的不足,而且是数字控制、非线性控制、最优控制、飞行器控制和智能产品设计的入门课程。许多的后续课程还包括了大量实验。在学习本课程之前,要求掌握动态系统或者电路分析和拉普拉斯变换的知识。

学习反馈控制课程的前提

本书针对所有工科专业高年级学生。对于第 4 章至第 7 章的核心内容,对建模和动态响应的理解是必备知识。通过之前的物理学、电路和动态响应课程学习,许多学生已经具有足够的背景知识来学习这门课程。对于需要复习的学生,第 2 章和第 3 章可以弥补这一漏洞。

理解矩阵代数是理解状态空间的基础。尽管通过之前的数学课,所有的学生都有这方面的知识,附录 C 还是列出了它的基本关系,对控制系统特定内容的运算也在第 7 章的开始部分给出。重点是线性动态系统和线性代数的关系。

补充

前述网页载有可以输出本书所有 MATLAB 图形的 m 文件,这些文件可以复制并由学生使用。

致谢

最后,我们向为反馈控制理论发展到今天这样激动人心的程度做出过贡献的学者,特别是给予我们巨大帮助和建议的学生、同事们致谢。尤其应该提到的是,我们在与斯坦福大学控制理论导论教师 A.E.Bryson, Jr.、R.H.Canon, Jr.、D.B.DeBra、S.Rock、S.Boyd、C.Tomlin 和 P.Enge 的讨论过程中受益匪浅。

还要特别地感谢为本书几乎全部的习题提供答案的同学们。

作者
加州斯坦福大学

Contents

1	An Overview and Brief History of Feedback Control	1
	A Perspective on Feedback Control	1
	Chapter Overview	1
	1.1 A Simple Feedback System	2
	1.2 A First Analysis of Feedback	5
	1.3 A Brief History	7
	1.4 An Overview of the Book	12
	Summary	13
	End-of-Chapter Questions	14
	Problems	14
2	Dynamic Models	17
	A Perspective on Dynamic Models	17
	Chapter Overview	17
	2.1 Dynamics of Mechanical Systems	18
	2.2 Models of Electric Circuits	28
	2.3 Models of Electromechanical Systems	31
	▲2.4 Heat and Fluid-Flow Models	36
	▲2.5 Complex Mechanical Systems	45
	Summary	49
	End-of-Chapter Questions	49
	Problems	50
3	Dynamic Response	58
	A Perspective on System Response	58
	Chapter Overview	58
	3.1 Review of Laplace Transforms	58
	3.2 System Modeling Diagrams	80
	3.3 Effect of Pole Locations	84
	3.4 Time-Domain Specifications	90
	3.5 Effects of Zeros and Additional Poles	94
	3.6 Amplitude and Time Scaling	98
	3.7 Stability	100
	▲3.8 Obtaining Models from Experimental Data	108
	▲3.9 Mason's Rule and the Signal-Flow Graph	109
	Summary	112
	End-of-Chapter Questions	113
	Problems	114
4	Basic Properties of Feedback	127
	A Perspective on the Properties of Feedback	127
	Chapter Overview	127
	4.1 The Basic Equations of Control	128

2 Contents

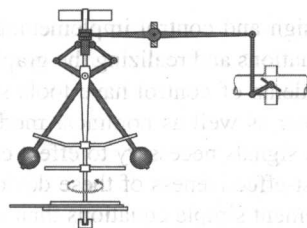
4.2	Control of Steady-State Error: System Type	134
4.3	Control of Dynamic Error: PID Control	142
▲ 4.4	Extensions to the Basic Feedback Concepts	146
	Summary	160
	End-of-Chapter Questions	161
	Problems	161
5	The Root-Locus Design Method	177
	A Perspective on the Root-Locus Design Method	177
	Chapter Overview	177
5.1	Root Locus of a Basic Feedback System	178
5.2	Guidelines for Sketching a Root Locus	182
5.3	Selected Illustrative Root Loci	191
5.4	Selecting the Parameter Value	201
5.5	Design Using Dynamic Compensation	203
5.6	A Design Example Using the Root Locus	210
5.7	Extensions of the Root-Locus Method	215
	Summary	222
	End-of-Chapter Questions	223
	Problems	224
6	The Frequency-Response Design Method	239
	A Perspective on the Frequency-Response Design Method	239
	Chapter Overview	239
6.1	Frequency Response	240
6.2	Neutral Stability	256
6.3	The Nyquist Stability Criterion	258
6.4	Stability Margins	267
6.5	Bode's Gain-Phase Relationship	272
6.6	Closed-Loop Frequency Response	275
6.7	Compensation	276
▲ 6.8	Alternative Presentations of Data	295
▲ 6.9	Specifications in Terms of the Sensitivity Function	299
▲ 6.10	Time Delay	305
	Summary	307
	End-of-Chapter Questions	309
	Problems	310
7	State-Space Design	329
	A Perspective on State-Space Design	329
	Chapter Overview	329
7.1	Advantages of State Space	330
7.2	System Description in State Space	331
7.3	Block Diagrams and State Space	336
7.4	Analysis of the State Equations	339
7.5	Control-Law Design for Full-State Feedback	355
7.6	Selection of Pole Locations for Good Design	366
7.7	Estimator Design	374

7.8	Compensator Design: Combined Control Law and Estimator	385
7.9	Introduction of the Reference Input with the Estimator	396
7.10	Integral Control and Robust Tracking	406
▲ 7.11	Loop Transfer Recovery (LTR)	420
▲ 7.12	Direct Design with Rational Transfer Functions	424
▲ 7.13	Design for Systems with Pure Time Delay	427
	Summary	431
	End-of-Chapter Questions	432
	Problems	434
8	Digital Control	452
	A Perspective on Digital Control	452
	Chapter Overview	452
	8.1 Digitization	452
	8.2 Dynamic Analysis of Discrete Systems	454
	8.3 Design Using Discrete Equivalents	460
	8.4 Hardware Characteristics	468
	8.5 Sample-Rate Selection	471
▲ 8.6	Discrete Design	473
▲ 8.7	State-Space Design Methods	479
	Summary	485
	End-of-Chapter Questions	486
	Problems	487
9	Nonlinear Systems	497
	Perspective on Nonlinear Systems	497
	Chapter Overview	497
	9.1 Introduction and Motivation: Why Study Nonlinear Systems?	498
	9.2 Analysis by Linearization	499
	9.3 Equivalent Gain Analysis Using the Root Locus	505
	9.4 Equivalent Gain Analysis Using Frequency Response: Describing Functions	513
▲ 9.5	Analysis and Design Based on Stability	522
	Summary	537
	End-of-Chapter Questions	537
	Problems	538
10	Control System Design: Principles and Case Studies	545
	A Perspective on Design Principles	545
	Chapter Overview	545
	10.1 An Outline of Control Systems Design	545
	10.2 Design of a Satellite's Attitude Control	550
	10.3 Lateral and Longitudinal Control of a Boeing 747	561
	10.4 Control of the Fuel–Air Ratio in an Automotive Engine	574
	10.5 Control of the Read/Write Head Assembly of a Hard Disk	580
	10.6 Control of Rapid Thermal Processing (RTP) Systems in Semiconductor Wafer Manufacturing	586
	Summary	597

4 Contents

End-of-Chapter Questions	599
Problems	599

1 An Overview and Brief History of Feedback Control



A Perspective on Feedback Control

Control of dynamic systems is a very common concept with many characteristics. A system that involves a person controlling a machine, as in driving an automobile, is called **manual control**. A system that involves machines only, as when room temperature can be set by a thermostat, is called **automatic control**. Systems designed to hold an output steady against unknown disturbances are called **regulators** while systems designed to track a reference signal are called **tracking** or **servo** systems. Control systems are also classified according to the information used to compute the controlling action. If the controller does *not* use a measure of the system output being controlled in computing the control action to take, the system is called **open-loop control**. If the controlled output signal *is* measured and fed back for use in the control computation, the system is called closed-loop or **feedback control**. There are many other important properties of control systems in addition to these most basic characteristics. For example, in this book we will mainly be concerned with controlling processes that can be adequately described by **linear, time-invariant** equations, whereas all physical processes are nonlinear if the signals are large and their characteristics vary with time if observed for a long time. We will also mainly consider feedback of the present output only, but a very familiar example illustrates the limitation imposed by that assumption. When driving a car, the use of simple feedback corresponds to driving in a thick fog where one can *see only the road immediately at the front of the car* and is unable to see the future required position! Looking at the road ahead is a form of predictive control, and this information, which has obvious advantages, would always be used where it is available, but in most automatic control situations studied in this book observation of the future track or disturbance is not possible. In any case, the control designer should study the process to see if any sensor could anticipate either a track to be followed or a disturbance to be rejected. If such a possibility is feasible, the control designer should use it to **feed forward** an early warning to the control system. An example of this is in the control of steam pressure in the boiler of an electric power generation plant. A measure of the *electric* power demand at the output of the plant can be fed forward to the boiler controller in anticipation of a soon-to-be demanded increase in steam flow.

Chapter Overview

In this chapter we begin our exploration of feedback control using a simple familiar example: a household furnace controlled by a thermostat. The generic components of a control system are identified within the context of this example. In another example—an automobile cruise control—we develop the elementary static equations and assign numerical values to elements of the system model in order to compare the performance of open-loop control to that of feedback control when dynamics are ignored. In order to provide a context for our studies and to give you a glimpse of how the field has evolved, Section 1.3 provides a brief history of control theory and design. Finally, Section 1.4 provides a brief overview of the contents and organization of the entire book.

The evolution of cheap and powerful digital computers has had a major impact on control

design and control implementation. Software such as MATLAB is a great aid to solving the equations and realizing the graphics of control design methods. For analyzing system response, students of control have tools such as Simulink[®], which can easily compute the response of linear as well as nonlinear models of processes and controls. The controllers which compute the signals necessary to effect control are mainly electronic units because of the flexibility and cost-effectiveness of these devices. While analog units are typically faster and cheaper to implement simple equations than digital logic, the greater programming flexibility and increasing cost-effectiveness of embedded digital processors is causing them to become ever more common in controller implementation. The influence of these trends on our introduction to the stimulating field of control is evident throughout the text.

The applications of feedback control have never been more exciting than they are today. Landing and collision avoidance systems using the Global Positioning System (GPS) are now under development and promise a revolution in our ability to navigate in an ever more crowded airspace. In the magnetic data storage devices for computers known as hard disks, control of the read/write head assembly is often designed to have tracking errors on the order of microns and to move at speeds of a fraction of a millisecond. Control is essential to the operation of systems from cell phones to jumbo jets and from washing machines to oil refineries as large as a small city. The list goes on and on. In fact, many engineers refer to control as a *hidden technology* because of its essential importance to so many devices and systems while being mainly out of sight. The future will no doubt see engineers create even more imaginative applications of feedback control. Study of control problems over the past 200 years has led to an extensive body of knowledge common to both manual and automatic control which has evolved into the discipline of control systems design, the subject of this book.

1.1 A Simple Feedback System

In feedback systems the variable being controlled—such as temperature or speed—is measured by a sensor, and the measured information is fed back to the controller to influence the controlled variable. The principle is readily illustrated by a very common system, the household furnace controlled by a thermostat. The components of this system and their interconnections are shown in Fig. 1.1. The figure identifies the major parts of the system and shows the directions of information flow from one component to another.

We can easily analyze the operation of this system qualitatively from the graph. Suppose both the temperature in the room where the thermostat is located and the outside temperature are significantly below the reference temperature (also called the set point) when power is applied. The thermostat will be *on*, and the control logic will open the furnace gas valve and light the fire box. This will cause heat Q_{in} to be supplied to the house at a rate that will be significantly larger than the heat loss Q_{out} . As a result, the room temperature will rise until it exceeds the thermostat reference setting by a small amount. At this time the furnace will be turned off and the room temperature will start to fall toward the outside value. When it falls a small amount below the set point, the thermostat will come on again and the cycle will repeat. Typical plots of room temperature along with the furnace cycles of on and off are shown in Fig. 1.1. The outside temperature is 50°F and the thermostat is initially set at 55°F. At 6 A.M., the thermostat is stepped to 65°F, and the furnace brings it to that level and cycles the temperature around that figure thereafter.¹ Notice that the house is well insulated so that the fall of temperature with the

¹Notice that the furnace had come on a few minutes before 6 A.M. on its regular nighttime schedule.

furnace off is significantly slower than the rise with the furnace on. From this example we can identify the generic components of the elementary feedback control system as shown in Fig. 1.2.

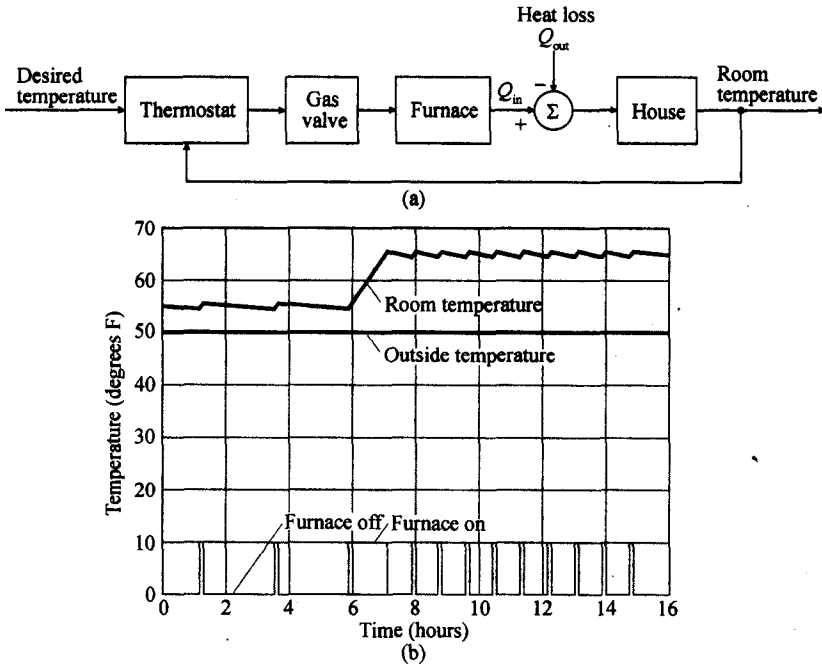


Figure 1.1 (a) Component block diagram of a room temperature control system; (b) Plot of room temperature and furnace action

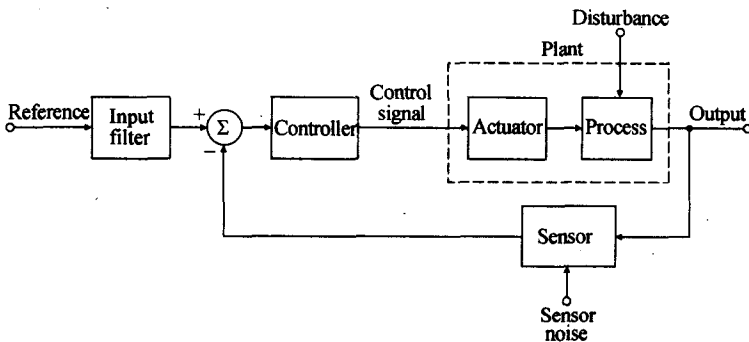


Figure 1.2 Component block diagram of an elementary feedback control

The central component of this feedback system is the **process** whose output is to be controlled. In our example the process would be the house whose output is the room temperature and the **disturbance** to the process is the flow of heat from the house due to conduction through the walls and roof to the lower outside temperature. (The outward flow of heat also depends on other factors, such as wind, open doors, etc.) The design of the process can obviously have a major impact on the effectiveness of the controls. The temperature of a well insulated house with